Multi-technique Studies of Ionospheric Plasma Structuring

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Award Number: N00014-03-10593

LONG-TERM GOALS

Understanding physical processes that lead to plasma structuring in the equatorial, mid and high-latitude ionosphere. Identifying the effects of such variability, generally known as ionospheric space weather, on the operation of various communication, navigation and surveillance systems.

OBJECTIVES

Establish major drivers that lead to structured ionospheric plasma in equatorial, mid and high-latitude regions. Investigate cascading of plasma structuring from large (~hundreds of km) to small (~tens of m) scales, which cause outages in space-based communication and GPS-based navigation systems.

APPROACH

Satellite communication and navigation systems operating at low latitudes suffer outages due to ionospheric scintillations during large magnetic storms that are not currently specified by any model. This report describes and demonstrates how in the framework of an eastward electric field penetration from high latitudes to low latitudes at dusk during the main phase of a large storm, for which the D_{st} index $\leq$ -100 nT and the rate of change of $D_{st} \leq$ -50 nT/hour, it is possible to specify the longitude interval within the low latitude ionosphere where scintillations and plasma bubbles are most likely to occur. It is known that the eastward prompt penetration electric field becomes enhanced near sunset due to the day-to-night conductivity gradient. Such enhanced eastward electric fields generally set off the Rayleigh-Taylor plasma instability at F-region heights and cause the formation of plasma bubbles and irregularities of electron density that give rise to scintillations of satellite signals. We have studied 30 large magnetic storms during Solar Cycle 23 which satisfy the two criteria mentioned above and attempted to specify the longitude interval of scintillation occurrence during the main phase of such storms. We have tracked globally the occurrence of equatorial scintillations during magnetic storms by the use of scintillation observations made by the Air Force Research Laboratory's SCINDA (Scintillation Network Decision Aid) network and the DMSP satellite in-situ measurements of plasma bubbles at 840 km. The statistical study reveals that during large magnetic storms, scintillations and plasma bubbles occur over a specific longitude sector for which the evening period corresponds to the time interval of the main phase of storms. This result overrides the climatological pattern of quiet-time variation of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE
Multi-technique Studies of Ionospheric Plasma Structuring

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston University,Center for Space Physics,725 Commonwealth Avenue,Boston,MA,02215

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

scintillation with longitude and season that shows an equinoctial maximum at all longitudes, a maximum in the December solstice over the Atlantic sector and a maximum in the June solstice over the Pacific sector. The storm-time response of the equatorial ionosphere discussed in the paper will be implemented in the SCINDA algorithm to enhance its capability to specify scintillations during large magnetic storms that impact DoD communications and navigation systems.

WORK COMPLETED

The above analysis has been completed and a manuscript is being prepared for publication in Radio Science. Two presentations on this work were given at the International Beacon Satellite Meeting in Boston in June 2007 and the URSI General Assembly in Chicago in August 2008.

RESULTS

A scheme was devised for the specification of equatorial scintillations during large magnetic storms. For this purpose, we performed a statistical study of the distribution of equatorial scintillations and plasma bubbles for 30 large magnetic storms during Solar Cycle 23. These were the only storms that satisfied the two selective criteria mentioned in the Approach Section during this solar cycle, namely, D_{st} minimum $\leq$ -100 nT and the rate of change of $D_{st} \leq$ -50 nT/hour. The result of this statistical study is presented in Figure 1. The duration of the main phase of each storm was determined from the time interval between UT_1 when $dD_{st}/dt \leq$ -50 nT/hour and UT_2 when the D_{st} minimum $\leq$ -100 nT was attained. An asterisk against a particular date in the ordinate signifies that the storm onset occurred the day before. As mentioned earlier, we expect that in the dusk sector, corresponding to the main phase time interval (UT_1 - UT_2), the eastward penetration electric field will be maximum which may set off plasma instabilities to cause scintillations and plasma bubbles. The dusk sector, based on the onset of equatorial scintillation, is found to be at the median local time of 2000 LT. The longitude interval of scintillations, $\lambda_1^o - \lambda_2^o$ where 2000 LT prevails over the time interval UT_1 - UT_2 may be expressed as,

$$[(2000 - UT_1) \times 15 - (2000 - UT_2) \times 15] = (\lambda_1^o - \lambda_2^o) \text{ east longitude} \qquad (1)$$

Scintillation observations indicate that the scintillation onset in the equatorial region occurs at the median local time of 2000 LT but it is actually dispersed between 1920 LT to 2040 LT. Considering this dispersion, we may express the longitude interval of scintillations ($\lambda_1^o - \lambda_2^o$), as follows,

$$[(1920 - UT_1) \times 15 - (2040 - UT_2) \times 15] = (\lambda_1^o - \lambda_2^o) \text{ east longitude} \qquad (2)$$

Figure 1 shows chronologically the duration of the main phase of 30 magnetic storms during Solar Cycle 23 that satisfied our criteria of fast rate of change of the D_{st} index and large negative values of the D_{st} minimum. It has been mentioned earlier that the median local time of the occurrence of equatorial scintillations is 2000 LT. In Figure 1, below the universal time axis, a derived longitude scale has been affixed such that at each UT, the dusk condition of 2000 LT prevails at the corresponding longitude. For example, the abscissa shows that at 12 UT the local time of 2000 hours will prevail at the derived longitude of 120 E.

The long-term studies of equatorial scintillation indicate that the onset of the post-sunset equatorial scintillation may occur as early as 1920 LT and as late as 2040 LT. In order to accommodate this variation in the onset of equatorial scintillation with one derived longitude scale defined above, we

extend the possible onset of the main phase earlier by 40 minutes and similarly delayed the defined end of the storm by 40 minutes. Scintillations or plasma bubbles are expected over the derived longitude interval where dusk conditions prevail during the duration of the main phase of any storm (Basu et al., 2001, 2005, 2007). Over each line representing the extended duration of the main phase, we affix a diamond symbol when a DMSP satellite detects a plasma bubble near the magnetic equator at the derived longitude. It symbolizes the appearance of plasma bubbles in the dusk sector corresponding to the main phase of the storm. The vertical line hatching of horizontal lines indicates that SCINDA sites were located at the derived longitude corresponding to the main phase of the storm and that the stations detected scintillations over the period of hatching. In the figure, we may observe that most horizontal lines indicating the main phase of storms are intercepted by diamonds or vertical hatching. This establishes that scintillations or plasma bubbles were detected in the dusk sector that corresponded to the main phase of the 30 storms depicted in the figure.

It should be mentioned that prior to the year 2001, there were only three SCINDA sites at Ancon, Peru, Antofagasta, Chile and Ascension Island in the South Atlantic. As such in the early years, the vertical hatchings are very sparse and occurred only when those three SCINDA sites were located in the dusk sector associated with the main phase of storms. After 2001, a total of eight SCINDA sites became operational and around 2004, three more sites were added that provided good longitude coverage of scintillation measurements. The figure shows that vertical hatching lines become more preponderant after 2001. It may be noted that during the solar minimum period, the ionospheric height decreases and the equatorial plasma bubbles often do not attain the DMSP satellite altitude of 840 km. As such, during the solar minimum period the density of the diamond symbols also decreases in Figure 1. Further, a few storms that satisfied our criterion of fast rate of change and reached the minimum D_{st} value close to -100 nT over many hours, such as, the storm of 19 October 1998, were not as effective in producing equatorial irregularities. In spite of a few such issues, overall the lines depicting the main phase of 30 storms are intercepted by diamonds or vertical hatching indicating that, following the equations discussed above, it is possible to specify the longitude interval within the low latitude ionosphere where scintillations and plasma bubbles are most likely to occur. Thus the algorithm provided in this paper will greatly improve our ability to specify the longitude interval over which scintillation occurs during the main phase of large magnetic storms. It is important to note that no such specification models currently exist.

IMPACT/APPLICATIONS

Upward **E x B** plasma drifts at dusk set off plasma instabilities to generate ionospheric irregularities of electron density that cause scintillations of satellite signals at VHF and form plasma bubbles that may be detected in the topside ionosphere by DMSP satellites. We showed that from knowledge of the duration (UT interval) of the main phase of a storm, it is possible to determine the dusk sector corresponding to the UT interval of the storm main phase and thereby specify the longitude interval over which bubbles and scintillations are to be detected. This study suggests a scheme which may be implemented in operational systems for specification of the longitude interval where scintillations and plasma bubbles are to be expected during the main phase of large storms**.** The storm-time response of the equatorial ionosphere discussed in this report will be implemented in the SCINDA algorithm to enhance its capability to specify scintillations during large magnetic storms that impact DoD communications and navigation systems.

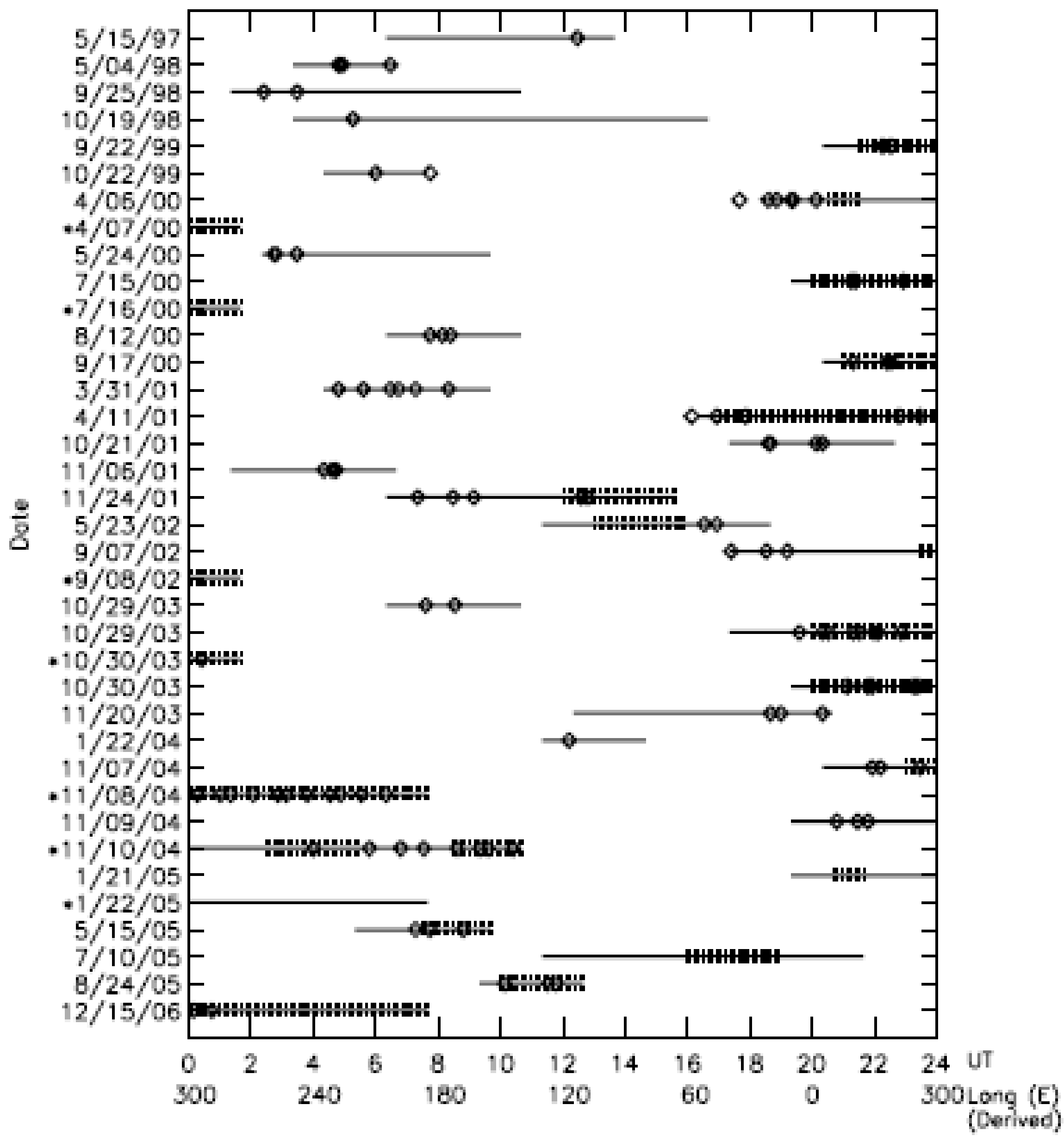

Figure 1 - Illustrates chronologically the duration, in UT, of the main phase of 30 intense magnetic storms during Solar Cycle 23. Below the abscissa indicating the UT, a derived longitude scale is affixed such that the dusk condition of 2000 LT prevails at the derived longitude for each UT. The derived longitude scale defines the longitude of the occurrence of scintillations if the onset of equatorial scintillations occurred at 2000 LT. Since the onset of equatorial scintillations varies from as early as 1920 LT to as late as 2040 LT, the lines depicting the duration of the main phase of each storm have been extended earlier by 40 minutes and delayed at the end of the storm by 40 minutes in order that the derived longitude scale will correctly define the location of equatorial scintillations that is dispersed 40 minutes around 2000 LT. The diamond symbols indicate the detection of plasma bubbles by DMSP satellites in the dusk sector corresponding to the main phase of the storm. The vertical hatchings signify the time period over which the 250 MHz scintillations were detected by SCINDA sites in the dusk sector.

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